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# Optimal Sizing of PV-Battery for Loss Reduction and Intermittency Mitigation

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**Abstract**— Over these years, dependency of electric generation on renewables is increasing steadily. The renewable energy sources are usually connected to the electric grid on the distribution networks. Energy supply from prominent renewable sources like wind and solar are restricted due to the high level of unpredictability and intermittency associated with them. This leads to the inefficient and less reliable output from these sources. Thus proper generation prediction, sizing and intermittency mitigation of renewable energy sources such as wind and solar photovoltaic (PV) is necessary while placing them on the feeder. As these sources are distributed energy sources, the loss minimization can be one of the opportunities in addition to their generation support. This paper deals with the optimal sizing of solar PV and battery combination in a grid connected system. Solar PV generation is seen as the future generation source and battery storage with its matured technology can support it to become more reliable source in a power system. Here an analytical method for sizing of solar PV and battery is proposed. The line losses and intermittency minimization is the prime consideration for the sizing and placement of the solar PV and battery. To tackle with the variability of the solar PV generation, it is predicted by probability density function and supported by battery energy storage. The battery energy storage is properly sized to satisfy the state of charge limitations. The location and sizing methodology is applied to a 13-bus test system using MATLAB. With the proposed optimal sizing methodology the losses can be reduced up to 83 % during the solar PV generation period and a small amount of battery support can help to get constant power supply to the grid from the solar PV.

**Keywords**- Solar PV generation, beta probability density function, PV sizing, battery storage, State of charge, line loss reduction.

## I. INTRODUCTION

Renewable energy sources have been identified as one of the key electric supply sources to meet the ever increasing demand. However, intermittency and unpredictability associated with the prominent sources of renewable energy, viz. wind and solar are offering challenges to the normal operation power systems. This intermittency can be mitigated by integrating energy storage to the system at appropriate locations. As the investment costs associated with energy storage are high and grid scale storage technologies are yet to mature, there is a need to evaluate the quantum of energy storage that can be integrated with the grid to mitigate supply intermittency [1, 2]. This economic feasibility and quantum can be evaluated considering the loss of power supply probability or to maximize cost benefits of storage in grid

connected and islanded modes [3, 4, 5]. This would help the utilities to minimize the cost of supplying electricity, as well as the charges customer would have to pay [6]. Considering the high temporal intermittency associated with generation and limits on storage size, storage capacities are usually calculated for short term supplies only [7]. Optimal size and allocation of energy storage helps for operational planning of the system with large amount of renewables [8]. Inherent intermittency of solar power is the main challenge in maintaining the power quality and reliability and battery energy storage can provide a feasible solution [9, 10, 11].

Considering the high intermittency of solar PV and its planning issue related to sizing, this paper gives an analytical approach to obtain optimal sizing of solar PV generation and battery in a grid connected system. This optimal sizing methodology helps to reduce line losses and minimize intermittency of solar PV generation. The historical solar irradiance data is used to generate the beta probability density function and predicted solar PV generation is obtained from it. The varying generation is supported by battery energy storage. The proposed simple algorithm gives the optimal sizing of PV-battery combination.

## II. SOLAR PHOTOVOLTAIC GENERATION

Solar photovoltaic generation is intermittent in nature and it is a random function of solar irradiance. This behavior of randomness of solar irradiance can be expressed by  $\beta$  - probability density function ( $\beta$  -pdf) [12]. The expected solar PV output is calculated as below,

$$f_{\beta}(s) = \begin{cases} \frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha)\Gamma(\beta)} s^{(\alpha-1)} (1-s)^{(\beta-1)} & 0 \leq s \leq 1, \alpha, \beta \geq 0 \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

where,

$\Gamma$  gamma function;

$s$  random variable of solar irradiance in kW/m<sup>2</sup>

$f_{\beta}(s)$  Beta probability density function of  $s$ ;

$\alpha$  and  $\beta$  are the parameters of the Beta distribution function as given below,

$$\beta = (1 - \mu) \left( \frac{\mu(1 - \mu)}{\sigma^2} - 1 \right) \quad (2)$$

$$\alpha = \frac{\mu\beta}{1 - \mu} \quad (3)$$

where,

$\mu, \sigma$  mean and standard deviation of  $s$  respectively;

The probability of solar irradiance for any specific hour can be calculated by integrating the probabilities of each state during that hour as given below,

$$P_s(y) = \int_{y_1}^{y_2} f_\beta(s) ds \quad (4)$$

where,

$P_s(y)$  probability of solar irradiance in state  $y$ ;

$y_1, y_2$  solar irradiance limits of state  $y$ ;

Once the beta probability density function for the specific time period is calculated the output power of the solar module can be calculated using following equations [12],

$$T_{cy} = T_a + s_{ay} \left( \frac{N_{OT} - 20}{0.8} \right) \quad (5)$$

$$I_y = s_{ay} [I_{sc} + K_i (T_c - 25)] \quad (6)$$

$$V_y = V_{oc} - K_v * T_{cy} \quad (7)$$

$$ff = \frac{V_{MPP} * I_{MPP}}{V_{oc} * I_{sc}} \quad (8)$$

$$P_o(s) = N * ff * V_y * I_y \quad (9)$$

where,

$T_{cy}$  cell temperature  $^{\circ}C$  during state  $y$ ;

$T_a$  ambient temperature  $^{\circ}C$ ;

$K_v$  voltage temperature coefficient  $V / ^{\circ}C$ ;

$K_i$  current temperature coefficient  $A / ^{\circ}C$ ;

$N_{OT}$  nominal operating temperature of cell in  $^{\circ}C$ ;

$ff$  fill factor;

$I_{sc}$  short circuit current in A;

$V_{oc}$  open circuit voltage in V;

$I_{MPP}$  current at maximum power point in A;

$V_{MPP}$  voltage at maximum power point in V;

$s_{ay}$  output power of of PV module in state  $y$ ;

$P_o(s)$  average solar irradiance of state  $y$ ;

This expected output can be used to calculate the optimal rating of solar PV and battery to minimize the losses and intermittency.

### III. BATTERY STATE-OF-CHARGE (SOC)

Solar photovoltaic generation has varying generation and this effect of changing nature of generation can be minimized by using battery support. The batteries are reliable source of power and energy and can supply the system whenever it is required. The battery SOC gives the available charge after

every charging or discharging. It is also a parameter which determines the battery life. A number of methods are available for the calculation of battery SOC [13]. Here ampere hour method is used for finding the state of charge [14]. This is a common SOC checking method where the charging and discharging is directly related to the current drawn or supplied by the battery. The SOC of a battery can be given as,

$$SOC = SOC_0 - \frac{1}{C_N} \int_{t_0}^t \delta(I) I_{Batt} dt \quad (10)$$

Where,

$SOC_0$  nominal SOC of battery;

$C_N$  rated capacity of battery;

$\delta(I)$  current loss coefficient;

$I_{Batt}$  battery current;

Ampere-hour(Ah) rating of the battery is determined and the limits of the SOC are checked. The SOC limits considered here are  $(0.20 \leq SOC \leq 1.0)$ . The battery rating is slightly modified if not within limits so as it will fulfil the SOC condition.

### IV. CALCULATION OF LINE LOSSES

The total active power loss in the distribution network is a function of the power injected from distributed generation based on the equivalent current injections. A bus -injection to branch- current (BIBC) matrix gives bus current injections and branch currents which is used for the calculation of total active power losses [15]-[16]. This calculated total power losses can be used to determine the optimum size of solar PV generation and battery storage. The method is given here briefly.

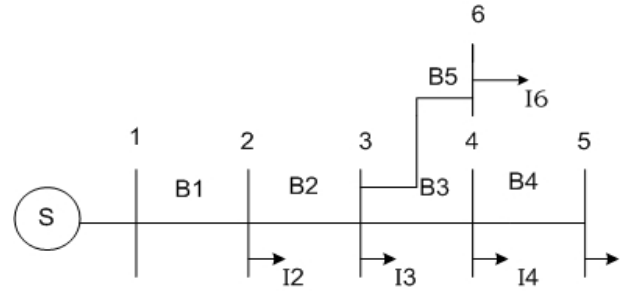


Figure 1: A simple radial feeder

Let the resistances of each branch be  $R_1, R_2, R_3, R_4$  and  $R_5$ . The currents flowing through each branch are denoted by  $B1, B2, B3, B4$  and  $B5$ . Total power loss  $P_L$  is sum of power losses in each branch,

$$P_L = \sum_{b=1}^B B^2 R \quad (11)$$

This power loss can be expressed in terms of load power instead of load-current. Using a general relation between power, voltage, current and power factor the conversion for current is obtained. The active power is expressed as,

$$P = \sqrt{3} V_L I_L \cos \phi \quad (12)$$

Load current in ampere can be expressed as,

$$I_L = \frac{P}{\sqrt{3}V_L \cos \phi} \quad (13)$$

The calculations of the power loss can be obtained using BIBC matrix method. The branch current B is calculated with the help of bus injection to branch-current matrix (BIBC). The elements of BIBC matrix can be calculated as,

$$\begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix} = \begin{bmatrix} I_2 + I_3 + I_4 + I_5 + I_6 \\ I_3 + I_4 + I_5 + I_6 \\ I_4 + I_5 \\ I_5 \\ I_6 \end{bmatrix} \quad (14)$$

$$\begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \end{bmatrix} \quad (15)$$

$$B = [BIBC][I] \quad (16)$$

The branch resistance vector is,

$$[R] = \begin{bmatrix} R_1 \\ R_2 \\ R_3 \\ R_4 \\ R_5 \end{bmatrix} \quad (17)$$

$$P_{loss} = B_1^2 R_1 + B_2^2 R_2 + B_3^2 R_3 + B_4^2 R_4 + B_5^2 R_5 \quad (18)$$

The above equation (18) can be written in general form for n number of buses as,

$$P_L = \sum_{i=1}^{nb} B_i^2 R_i \quad (19)$$

$$P_L = [R]^T [BIBC][I]^2 \quad (20)$$

The equation (20) can be used to calculate the losses of the system. The losses in the AC-DC conversion in the sizing methodology are neglected as they are less compared to the system

## V. SIZING AND LOCATION METHODOLOGY

The sizing and placement of the solar PV-battery very important considering the system losses. Distributed solar Generation should be properly sized and placed to reduce the system losses. In this methodology the varying solar PV generation is considered. The sizing of the solar PV generation and the battery is done to achieve intermittency reduction and maximum loss reduction for the grid connected system. The hourly solar PV generation data and load data is used to calculate the losses of the system. As the system is grid connected the load is supplied by the grid whenever there is not any solar PV generation. The system is as shown in the Fig.2.

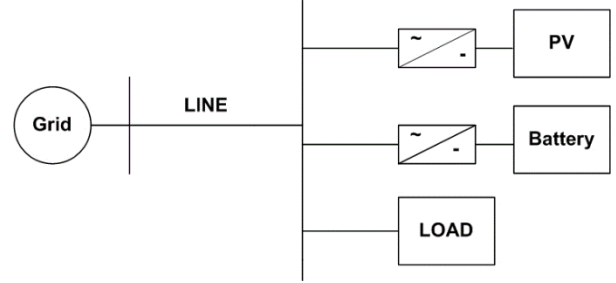


Fig. 2. Grid connected PV-battery system

### A. Location of Solar PV-battery

The distributed generation such as solar PV has advantages when connected to distribution system provide the power and voltage support and minimize the power losses in the system. The commonly used and simple location methodology of DG placement can be applied for the location of solar PV-battery. When the system is a simple radial network then 2/3 rule [15] can be easily applied and when the system is not a simple radial network the loss sensitivity factor method [19] can be used. The 2/3 rule is primarily used in capacitor placements in distribution systems. For a feeder with uniform kVAR load the 2/3 rule is as, 'the best capacitor size is 2/3 of the kVAR load, located 2/3 of the distance out the feeder'. This 2/3 rule is well applied to the placement of the distributed generation. Here the hourly load is considered to be uniformly distributed along the feeder and hence the 2/3 rule can be applied.

### B. Sizing of Solar PV-battery

A simple sizing methodology can be applied for the solar PV generation and the battery. The sizing methodology is as given below:

1. With the help of 2/3 rule or loss sensitivity factor fix the optimal location of the solar PV generation.
2. Calculate the average load of system as,

$$L_{av} = (L_{h1} + L_{h2} + \dots + L_{h24}) / 24$$

3. Select a size of the solar photovoltaic generation ( $P_{dgpv}$ ) as X % of total load and calculate the actual hourly output of the PV generation ( $P_{pvh}$ ) for the selected size of solar PV, as given in equation (1-9).

- For each hour, calculate the battery power support ( $P_{bh}$ ) required for the solar PV generation to reduce the variation in the solar PV output such as,

$$P_{dgpv} = P_{pvh} + P_{bh}$$

- Using the battery watt-hour rating, total ampere hour rating of battery is calculated as,

$$B_{Ah} = \sum_{h=1}^H I_b \quad \text{Here } H=10 \text{ hours.}$$

Slightly change this rating if required so as it will not violate the SOC limits ( $0.20 \leq SOC$ ) during discharging for any hour as well as the whole discharging period.

- Once the solar PV size and battery size is calculated, the losses can be calculated for the hourly combination of solar PV and battery.
- Repeat the steps from (3) to (6) for different sizes of solar PV generation and battery and calculate the losses.
- Select the solar PV rating and related battery rating which gives minimum losses. This will give the optimum size of solar PV generation and battery.

The flowchart for the location and sizing methodology is as shown in Fig. 3. Here the reduction in

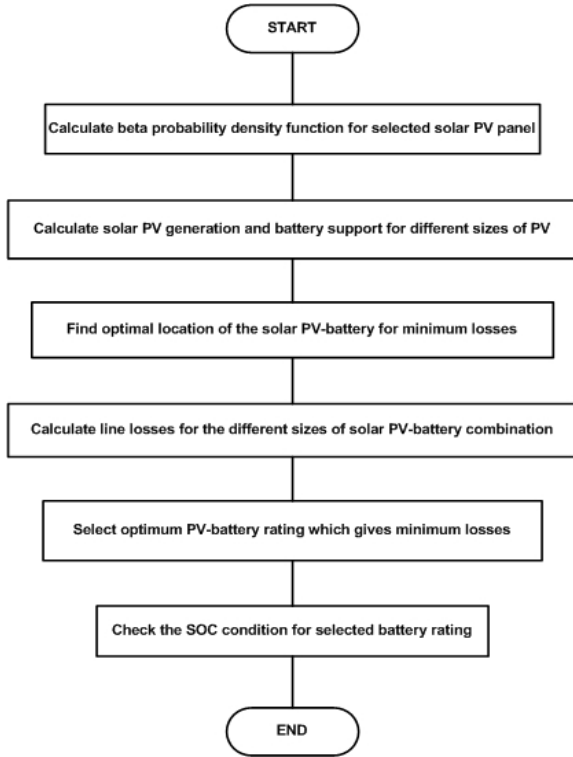


Fig. 3. Flowchart for location and sizing methodology

losses are calculated for the hours during which the solar PV and battery are in operation and the placement and sizing is

done accordingly. The battery is considered to be have only one charge and discharge cycle. The battery is fully charged during off-peak period, preferably during night and then supports the solar PV generation for intermittency mitigation and loss minimization

## VI. LOCATION AND SIZING SIMULATION

The above methodology is applied to a 13-bus test system [16], as system is shown in Fig.4.

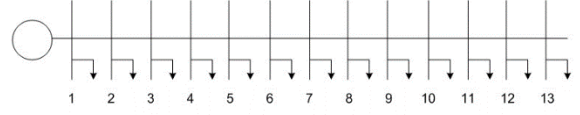


Fig. 4. 13-bus system

The hourly load data of Shahpura, Jaipur is considered here for the month of November [17], which is the load data for the 13- bus test system.

One year solar irradiance data for Jaipur is used to calculate the beta probability density function. The sufficient solar generation is available from 7 am to 6 pm. The expected solar generation is calculated for a typical day of the winter season. The mean and standard deviation values are shown in the Table I. The beta probability density functions are calculated for each hour.

TABLE I MEAN AND STANDARD DEVIATION

Time	Mean	Standard Deviation
8	0.367415	0.154400
9	0.518659	0.210628
10	0.569616	0.250715
11	0.609241	0.263780
12	0.632833	0.244981
13	0.637026	0.235276
14	0.609721	0.242638
15	0.550883	0.234876
16	0.458968	0.218465
17	0.313689	0.179889

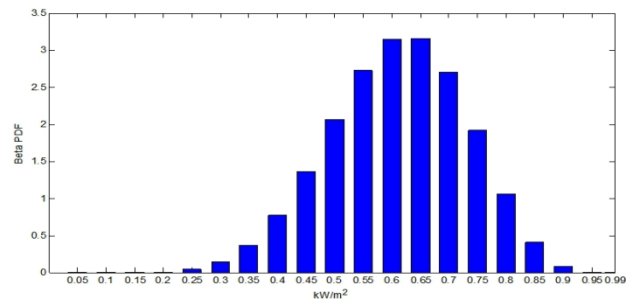


Fig. 5. Beta PDF for a typical hour

The beta probability density function for a typical hour is as shown in Fig.5.

The solar output is not considered during the extreme two intervals (6 am to 7 am, and 6 pm to 7 pm.) due to very low output. The solar panel considered is the KYOCERA- KD220GX-LPU panel [18]. The specification is given in Table II. The solar photovoltaic generation is calculated according to these specifications. The generation for the 10 hours for various sizes of PV is shown in Fig.6.

TABLE II ELECTRICAL SPECIFICATION:  
KYOCERA- KD220GX-LPU PANEL

	STC	NOCT	Temperature Coefficient
$V_{mp}(V)$	26.6	24.0	- 0.52
$I_{mp}(A)$	8.28	6.62	0.0065
$V_{oc}(V)$	33.2	30.4	- 0.36
$I_{oc}(A)$	8.98	7.27	0.060

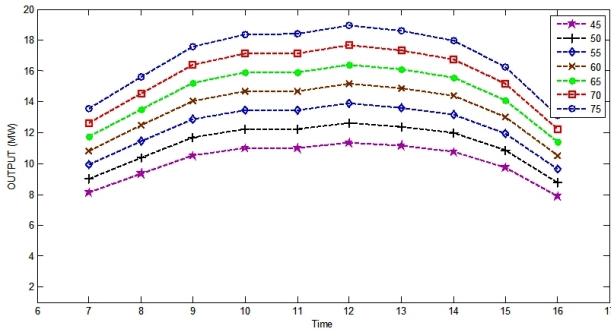


Fig. 6. Solar PV generation for various sizes

The base case losses of the system are calculated considering only the active power losses. Using the above location and sizing methodology, the location for the solar photovoltaic generation is at bus number 9. The losses of the system are calculated when the solar irradiation is available (7 am. to 6 pm.) during the 10 hours and the corresponding battery sizing is also done. The required current that should be supplied to compensate for the varying output of the photovoltaic generation is shown in Fig.7. The hourly losses for the various sizes of the solar photovoltaic generation & battery are shown in Fig.8.

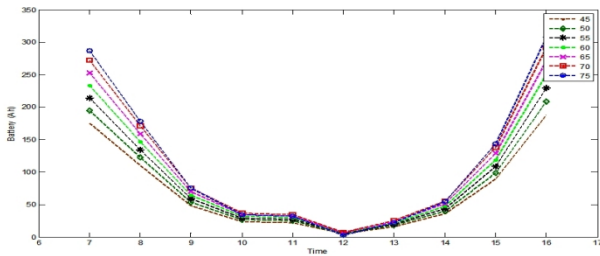


Fig. 7. Battery current for different solar PV sizes

The total system losses for different sizes of solar PV-battery combination are shown in Fig.9. It is seen that the losses at

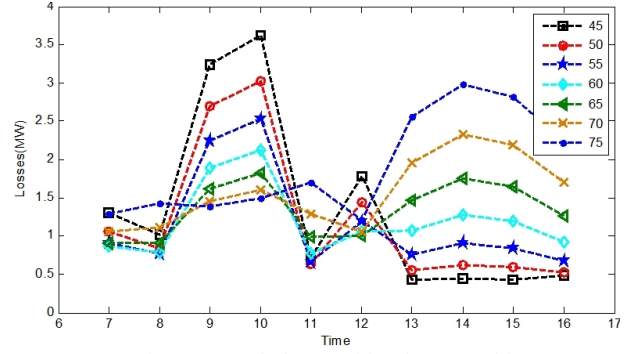


Fig. 8. Hourly losses with solar PV and battery

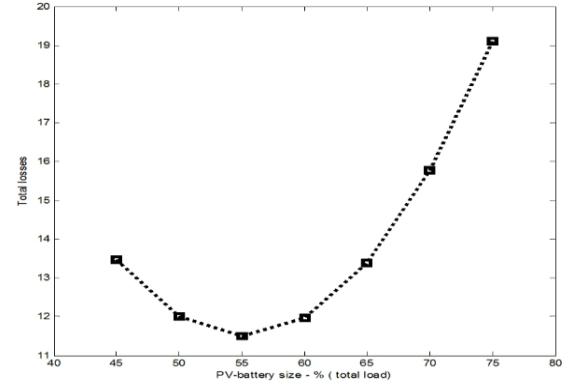


Fig. 9. Total losses with different sizes of PV and battery

55% size of solar PV-battery are minimum. This will give the optimal size of Solar PV and battery. The losses at optimal size are shown in Fig.10. With the optimal size the loss reduction is found to be 83 % for the hours during which the

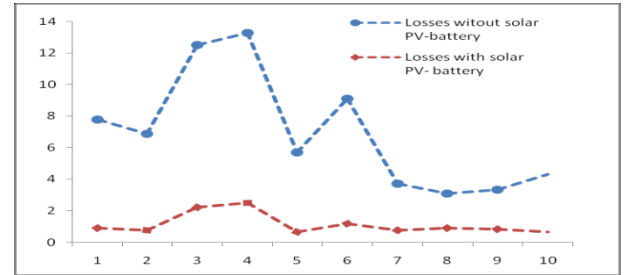


Fig. 10. Loss reduction with optimal size and location of PV-battery

PV and battery is connected. The battery support helps to mitigate the intermittency the solar generation as shown in Fig.11. The state of charge (SOC) of the battery for the optimal size and location is given in Fig. 12. The battery rating satisfies the condition of discharge with  $SOC \geq 0.2$ . The results for optimal size and location of solar PV and battery are given in Table III.

TABLE III RESULTS FOR OPTIMAL SIZING AND LOCATION

Optimal Location	Solar PV Rating (MW)	Battery rating (Ah)
Bus 9	14	995

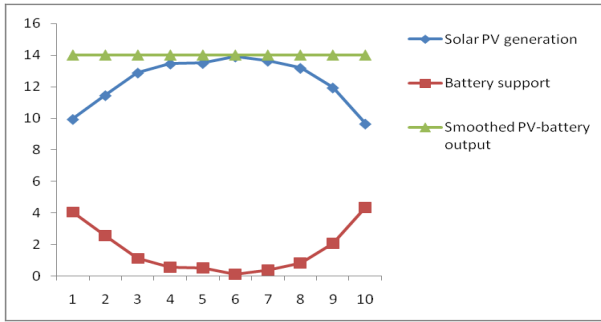


Fig. 11. Battery support for intermittency mitigation

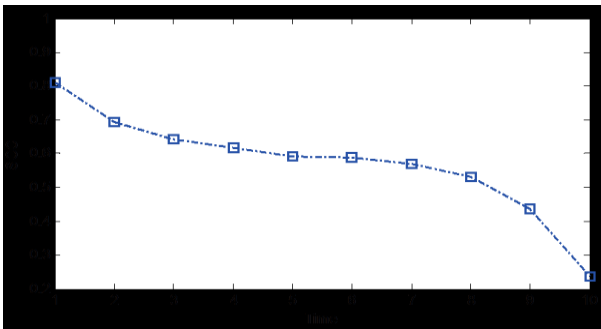


Fig. 12. SOC at optimal battery size

## VII. CONCLUSION

The solar photovoltaic generation is variable in nature. The expected output of such a solar PV generation can be calculated by the beta probability density function. The sizing of solar PV with variable output can be done with a simple methodology and the intermittency is minimized by battery energy storage. The placement can be fixed by the 2/3 rule. The optimal battery sizing considering the SOC can help to minimize power losses and reduce intermittency. The proposed sizing method can be used for the planning of solar PV generation with battery energy storage. The optimal sizing and placement with multiple solar PV generation can be done as a future work.

## REFERENCES

- [1] Shaghayegh Bahramirad, Wanda Reder, Amin Khodaei, "Reliability-constrained optimal sizing of energy storage system in a microgrid", *IEEE Transactions On Smart Grid*, vol. 3, no. 4, pp.2056- 2062, December 2012.
- [2] Joydeep Mitra, Mallikarjuna R. Vallem, "Determination of storage required to meet reliability guarantees on island-capable microgrids with intermittent Sources", *IEEE Transactions On Power Systems*, vol. 27, no.4, pp.2360- 2367, November 2012.
- [3] S.Bogdan,Borowy, Ziyad M. Salameh. "Methodology for optimally sizing the combination of a battery bank and PV array in a wind/PV hybrid system", *IEEE Transactions on Energy Conversion*, vol. 11, no. 2, pp.367-375, June 1996.
- [4] Tsung-Ying Lee. "Optimal capacity of the battery energy storage system in a power system", *IEEE Transactions on Energy Conversion*, vol. 8, no. 4, pp. 667-673, December 1993.
- [5] S. X. Chen. "Sizing of energy storage for microgrids", *IEEE Transactions on Smart Grid*, vol. 3, no. 1, pp. 142-151, March 2012.
- [6] Tsung-Y ing Lee. "Determination of optimal contract capacities and optimal sizes of battery energy storage systems for time-of-userates industrial customers", *IEEE Transactions on Energy Conversion*, vol. 10, no. 3, pp.562-568, September 1990.
- [7] W.D.Kellogg, M.H.Nehrir, G.Venkataramanan and V.Gerez, "Generation unit sizing and cost analysis for stand-alone wind, photovoltaic, and hybrid wind pv systems", *IEEE Transactions on Energy Conversion*, vol. 13, no. 1, pp.70-75, March 1998.
- [8] Changsong Chen, Shanxu Duan, Tao Cai, Bangyin Liu, Guozhen Hu, "Optimal allocation and economic analysis of energy storage system in microgrids", *IEEE Transactions on Power electronics*, vol. 26, no.10, pp. 6762-2773, October 2011.
- [9] Hill, Cody A., Matthew Clayton Such, Dongmei Chen, Juan Gonzalez, and W. Mack Grady,"Battery energy storage for enabling integration of distributed solar power generation", *IEEE Transactions on Smart Grid*, vol. 3, no.2, 850-857, June 2012.
- [10] Zhou, Haihua, Tanmoy Bhattacharya, Duong Tran, Tuck Sing Terence Siew, and Ashwin M. Khambadkone, "Composite energy storage system involving battery and ultracapacitor with dynamic energy management in microgrid applications", *IEEE Transactions on Power Electronics*, vol. 26, no.3, pp. 923-930, June 2011.
- [11] Traube, Joshua, Fenglong Lu, and Dragan Maksimovic, "Mitigation of Solar Irradiance Intermittency in Photovoltaic Power Systems With Integrated Electric-Vehicle Charging Functionality", *IEEE Transactions on Power Electronics*, vol. 28, no.6, pp. 3058-3067, June 2013.
- [12] Y. M. Atwa, E. F. El-Saadany, M. M. A. Salama, R. Seethapathy, "Optimal renewable resources mix for distribution system energy loss minimization", *IEEE Transactions on Power Systems*, vol.25, no.1, pp.360-370, February 2010.
- [13] Sabine Piller, Marrion Perrin, Andeas Joessen "Methods for state-of-charge determination and their applications", *Journal of Power sources*, Volume 96, Issue 1, pp. 113-120, 1 June 2001.
- [14] Martin Coleman, Chi Kwan Lee, Chunbo Zhu, and William Gerard Hurley "State-of-charge determination from emf voltage estimation: using impedance, terminal voltage, and current for lead-acid and lithium-ion batteries", *IEEE Transactions on Industrial Electronics*, vol. 54, no.5, pp. 2550-2557, October 2007.
- [15] H. L. Willis "Analytical methods and rules of thumb for modelling DG-distribution interaction", *IEEE*, 2000.
- [16] Gzel, Tuba Hocaoglu, M. Hakan; Eminoglu, Ulas; Balk, Abdl "Optimal placement and sizing of distributed generation on radial feeder with different static load models", *Future Power Systems,IEEE*,2005.
- [17] M. Rizwan, Dinesh Kumar, Rajesh Kumar, "Fuzzy logic approach for short term electrical load forecasting", *Electrical and Power Engineering Frontier*, Vol. 1, Issue. 1, pp. 8 -12, December 2012.
- [18] Available online: <http://www.kyocerasolar.com>
- [19] R. Srinivasa Rao, K. Ravindra, K.Satish and S.V.L. Narasimham, "Power loss minimization in distribution system using network reconfiguration in the Presence of Distributed Generation", *IEEE Transactions on Power Systems*, vol.28, no.1, pp.317-325, February 2013.